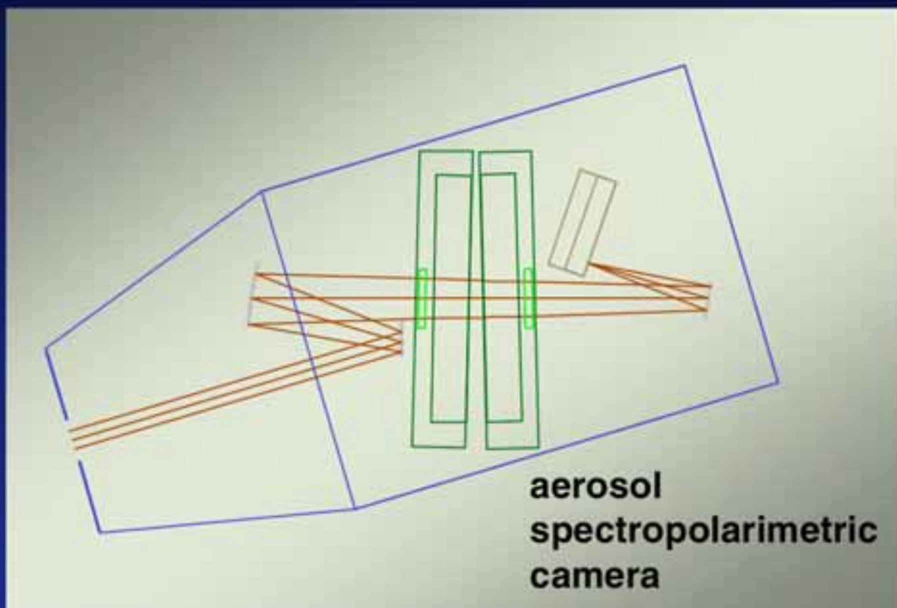
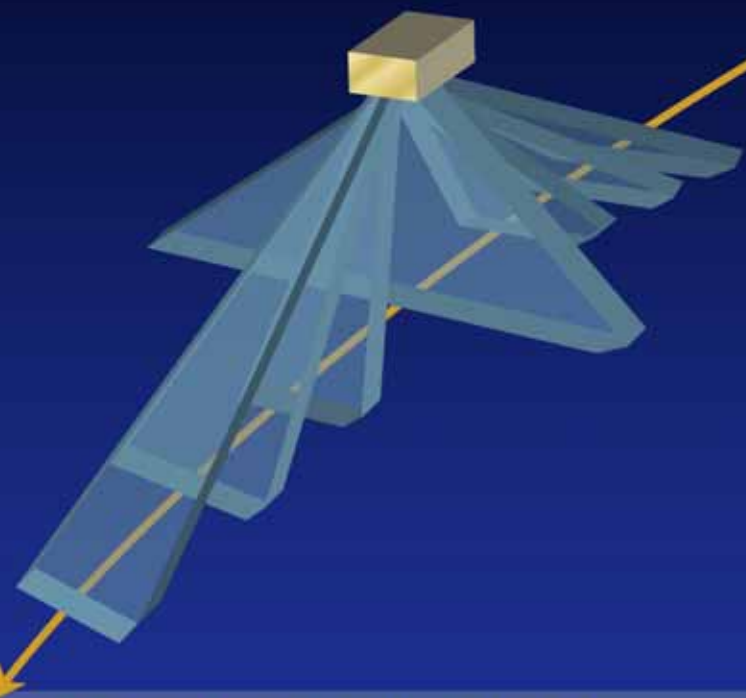
# Use of ultrafast polarization modulators for high-accuracy spectropolarimetric imaging of aerosols



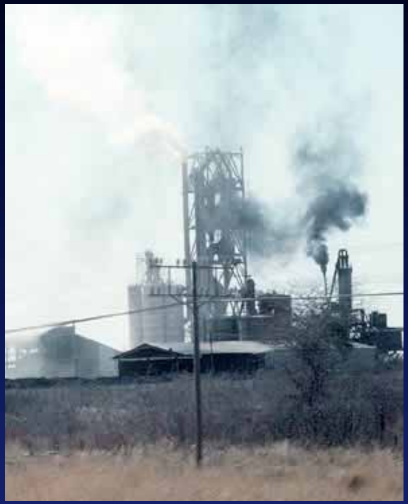



Russell Chipman, College of Optical Sciences, Univ. Arizona

David J. Diner (PI), Ab Davis, Thomas J. Cunningham, Gary Gutt, Bruce Hancock, Nasrat Raouf, Chao Sun, Yu Wang, Jason Zan – JPL
Neil Beaudry, U Arizona

ESTP, College Park, MD, 27 June 2006

# IIP Objectives and Vision



**Develop and provide proof-of-concept for an electro-optic imaging design, suitable for use in a space-borne multi-angle spectropolarimetric imaging (MSPI) aerosol sensor.**

**Integration of such data with surface and suborbital measurements would be used for determining aerosol effects on climate change and air quality, and for validating chemical and aerosol transport models.**

# IIP Objectives and Vision

Simultaneous flight with a high spectral resolution lidar (HSRL) will be a powerful next step in aerosol research after the A-Train.

The MSPI measurement objectives require very accurate measurements of the degree of linear polarization (0.5% DOLP uncertainty or less).

Static polarization filters do not provide sufficient accuracy and stability.

# The Aerosol Global Interactions Satellite (AEGIS) Concept

passive sensor heritage

MISR | MODIS | AATSR | APS | POLDER | TOMS

active sensor heritage

GLAS | CALIPSO

\+ **Technology developments**

ruggedized electro-optic modulators for high-accuracy, self-calibrated polarization imaging

355-nm laser output & receiver channels; scalable frequency-agile laser source suitable for space

**Multiangle SpectroPolarimetric Imager**

**High Spectral Resolution Lidar**

| Parameter | MSPI | HSRL |
|---|---|---|
| View angle range | Nadir to 70°, fore and aft | Nadir |
| Spectral range | Intensity: 380 - 2130 nm<br>Polarization: 650, 1610 nm<br>(0.5% uncertainty in DOLP) | HSRL: 355, 532 nm<br>Backscatter only: 1064 nm<br>Polarization: all three $\lambda$ |
| Spatial resolution of derived aerosol products | Horizontal: 1-2 km<br>Vertical: 200 m for plumes | Horizontal: 20 km<br>Vertical: 120 m (backscatter), 900 m (extinction) |
| Global coverage time (swath width) | Multiangle: 4 days (700 km)<br>“Nadir”: 1 day (2650 km) | NA (100 m) |

# Development effort rationale

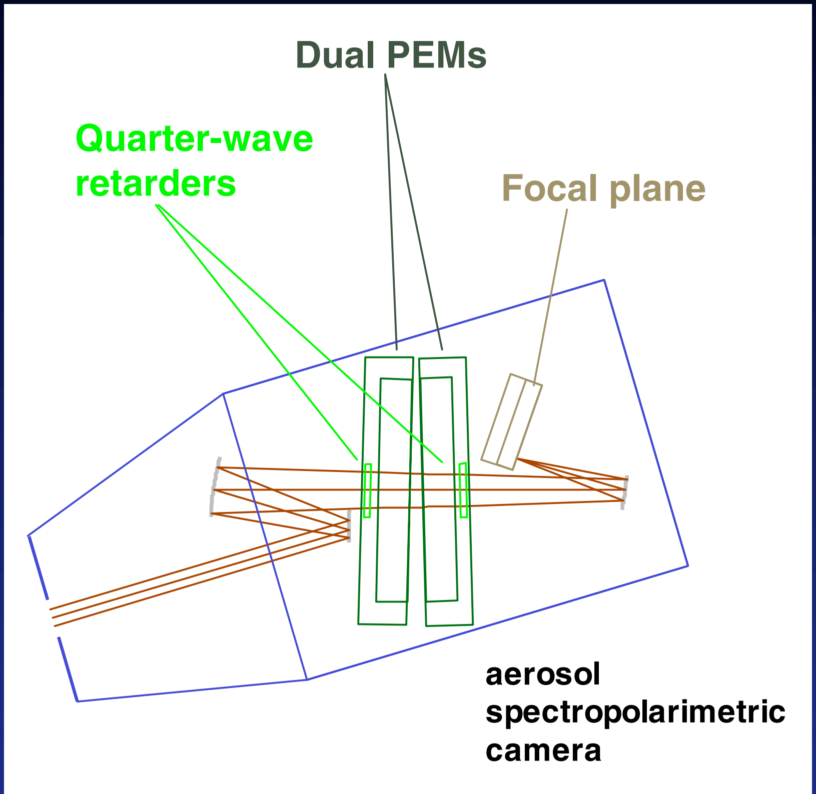
- Scattered light from the Earth is the sum of an unpolarized component and a polarized component, i.e., $I = I_{unpol} + I_{pol}$ .
- VNIR / SWIR intensities constrain particle size and shape, UV data are needed for aerosol absorption, and accurate polarimetry is required for real refractive index and particle size variance.
- Currently manifested satellite measurements do not combine these measurements with high spatial resolution and / or global coverage
- Developing new technology that makes this feasible.
  - MSPI measures unpolarized radiances in many bands and polarized radiances in two bands (650 and 1610 nm) simultaneously
- Measuring DOLP to 0.5% uncertainty is the most challenging requirement.
- Must be done without compromising the intensity measurement radiometric accuracies.

# Our dual-PEM imaging approach

Uses photo-elastic modulators (PEMs) to rapidly modulate the polarimetric portion of the incoming light.

A PEM consists of a glass bar bonded to piezoelectric transducer (PZT) that induces rapidly modulated stress birefringence at the resonant frequency of the bar (~42 kHz).

With two PEMs of slightly different frequencies in series, the signals at the focal plane through polarization analyzers are 0° and 45° are given by:




$$I_0 = 0.5 \{ I + Q \bullet J_0 [2\delta_0 \cos 1/2(\omega_1 - \omega_2)t] \}$$

$$I_{45} = 0.5 \{ I + U \bullet J_0 [2\delta_0 \cos 1/2(\omega_1 - \omega_2)t] \}$$

- the beat frequency is ~25 Hz (the line repeat time)
- I is intensity, which is unmodulated
- Q is preference for horizontal over vertical polarization
- U is preference for 45° over 135° polarization

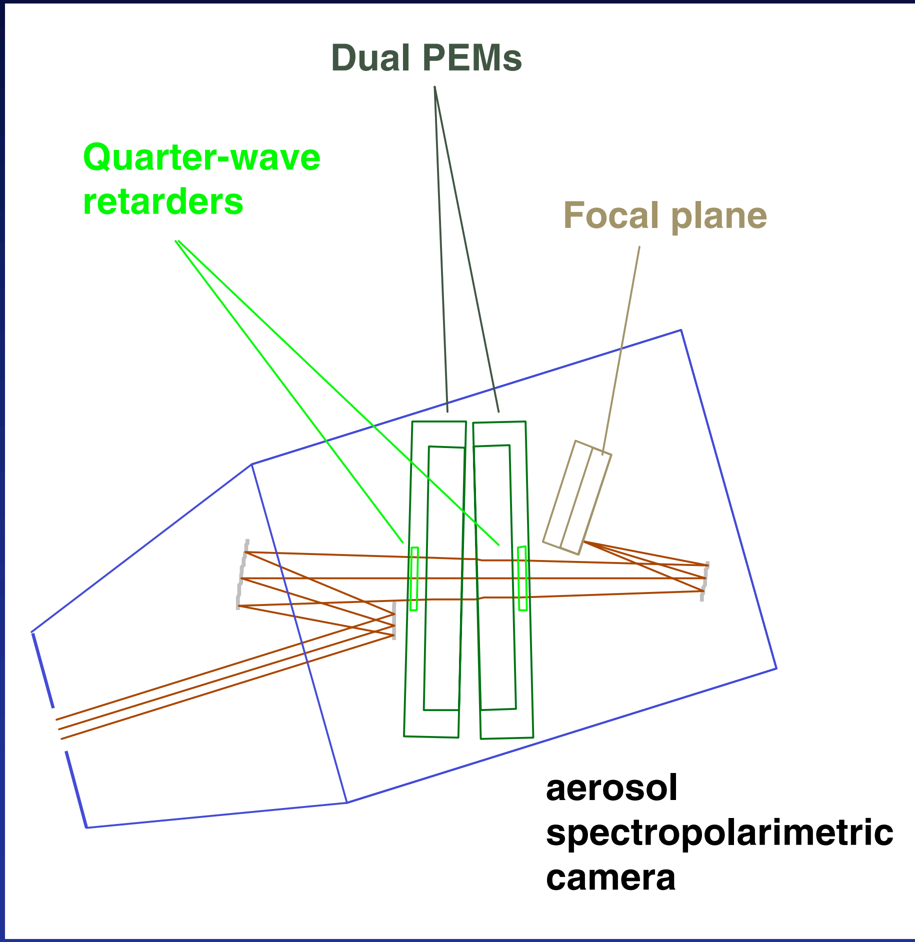
# Coordination of R&TD and IIP-4 efforts

**R&TD tasks aim to:**

- explore PEM design factors that affect integrity of output polarization signals
- demonstrate that a suitable CMOS focal plane detector system can be built
- demonstrate the detector noise characteristics

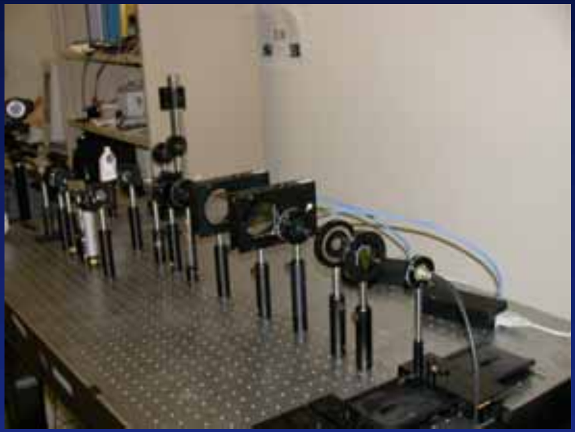
**IIP tasks:**

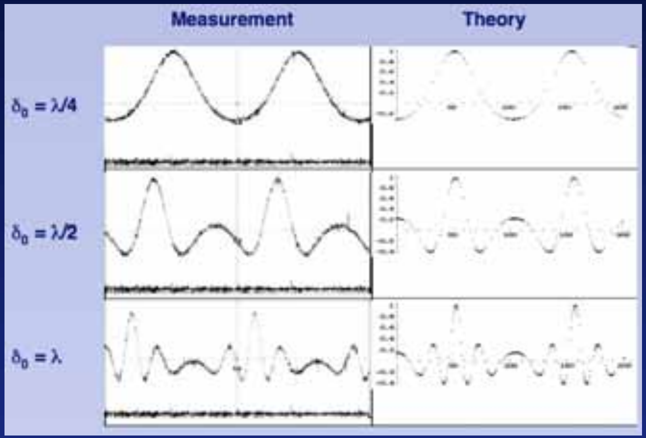
- develop launch-resilient design for the PEMs (in collaboration with PEM manufacturer, Hinds Instruments)
- demonstrate optical / polarimetric performance of the camera lens
- build and prove a lab demonstration camera system

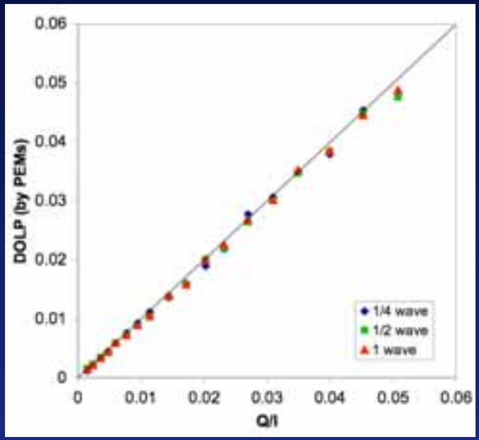


# R&TD progress

The dual-PEM modulation approach was experimentally demonstrated with excellent correspondence between theory and experiment



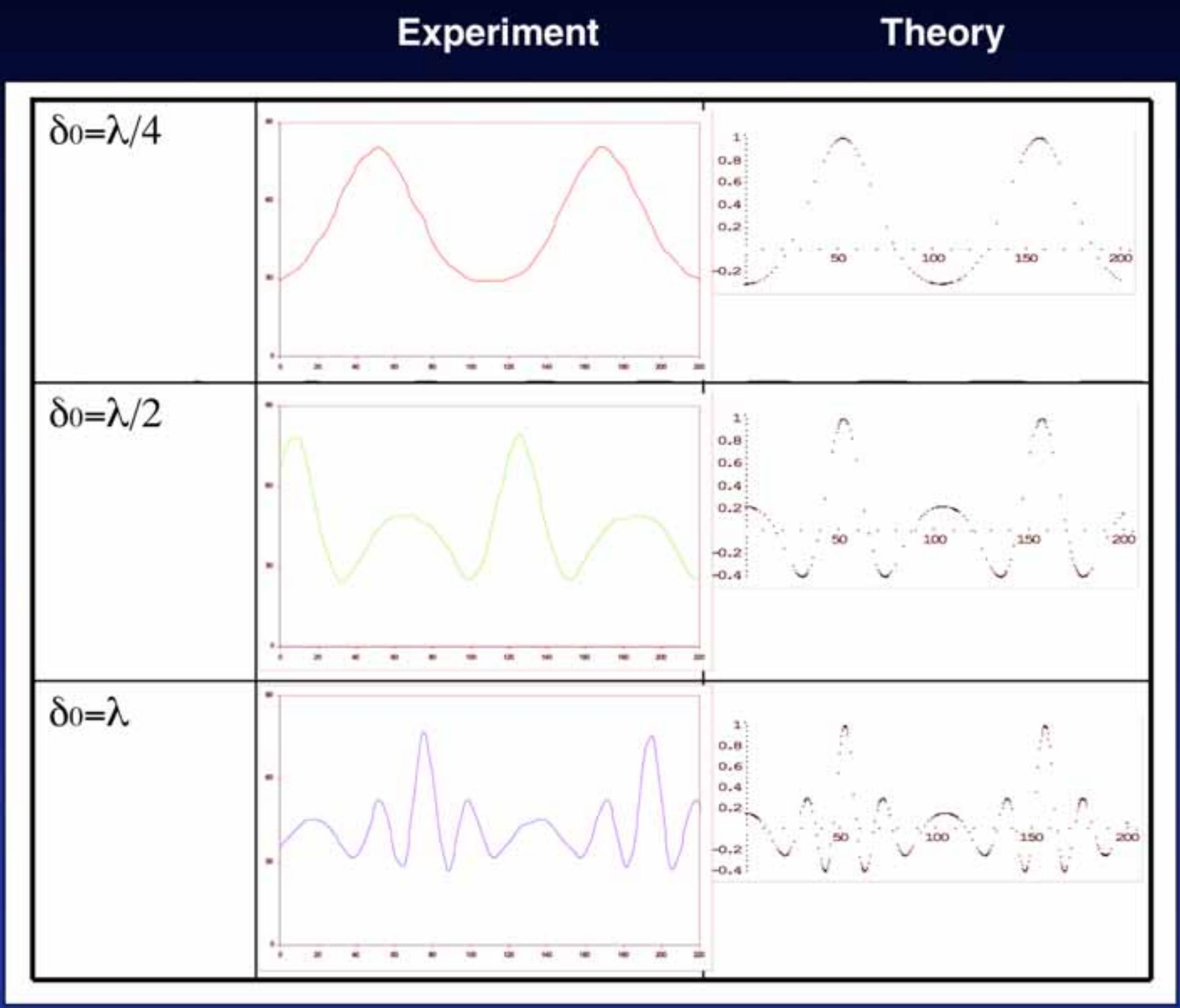


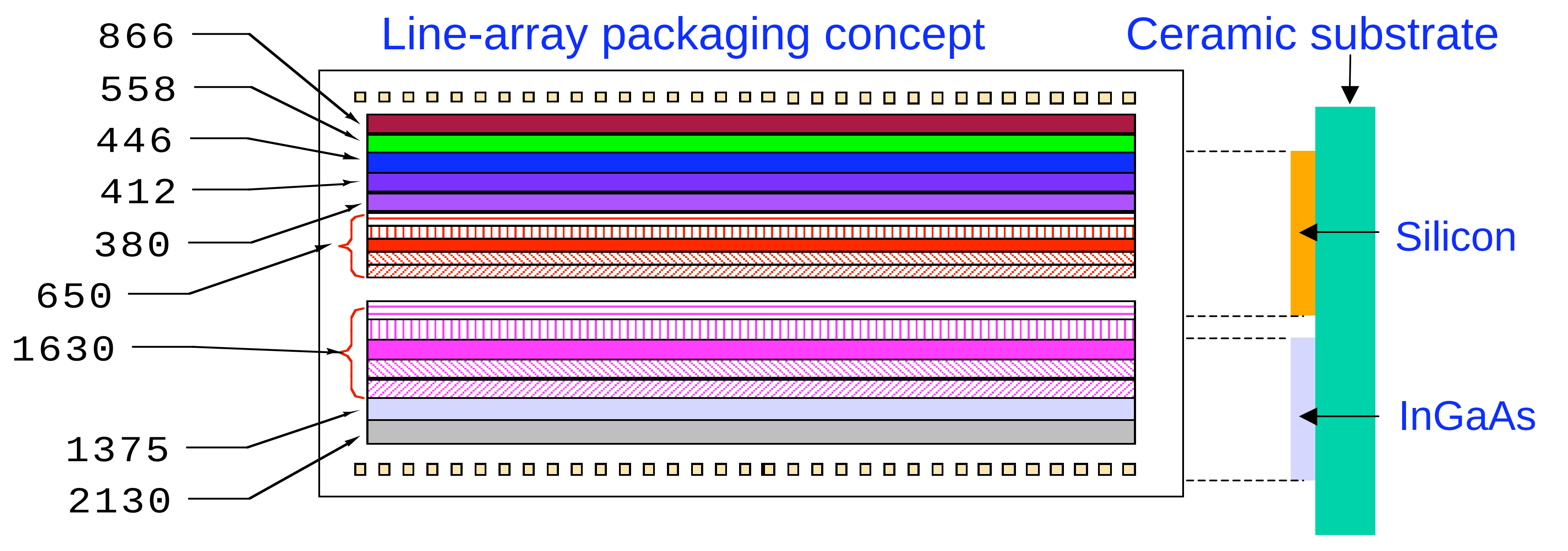

**Recent progress has focused on practical issues associated with implementing this modulation approach in a camera**

- In preparation for fabrication of a CMOS arrays for the short wavelength spectral bands
- achieving adequate signal-to-noise from space
- Modeling the dual-PEM performance in an imaging system: field-of-view effects and quarter-wave retarder design
- Synchronizing the signal processing to the PEM modulation

# PEM Experiments with Active Pixel Sensor



# CMOS line array design




- 10x10 μm pixels for UV-VIS
- 20x10 μm pixels for SWIR
- 1-msec sample rate
- Q.E. > 75%
- 140,000 electron full well
- 64 lines, 10x10 μm pixels on 16 μm pitch

In process: Detailed design and fabrication of the CMOS array for visible wavelength operation

# Signal-to-noise modeling

## System assumptions

- F/5.6 optics
- 10 μm x 10 μm detectors, with ~140,000 e- full wells
- maximum scene equivalent reflectance = 1.3
- 4% spectral bandwidth in the intensity channels, 8% in the polarization channels
- line repeat time ~40 msec

## Detector readout assumptions

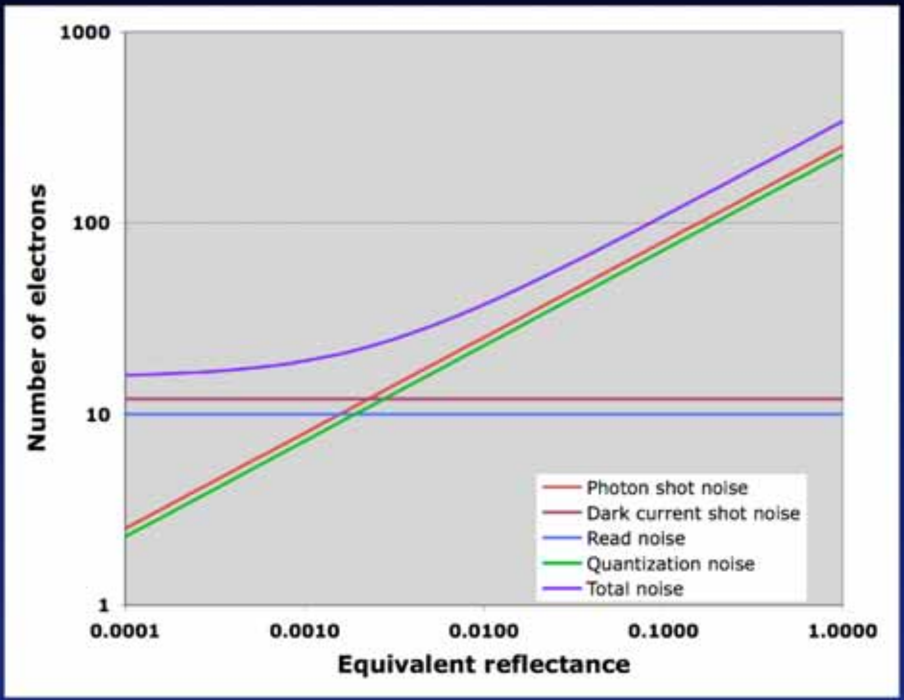
- performed every 1 msec in order to sample the polarization waveforms and to keep intensity signals below the detector full wells
- read noise 10 e- using correlated double sampling
- on-chip analog-to-digital conversion using 8-bit square-root encoding

## Modeling methodology

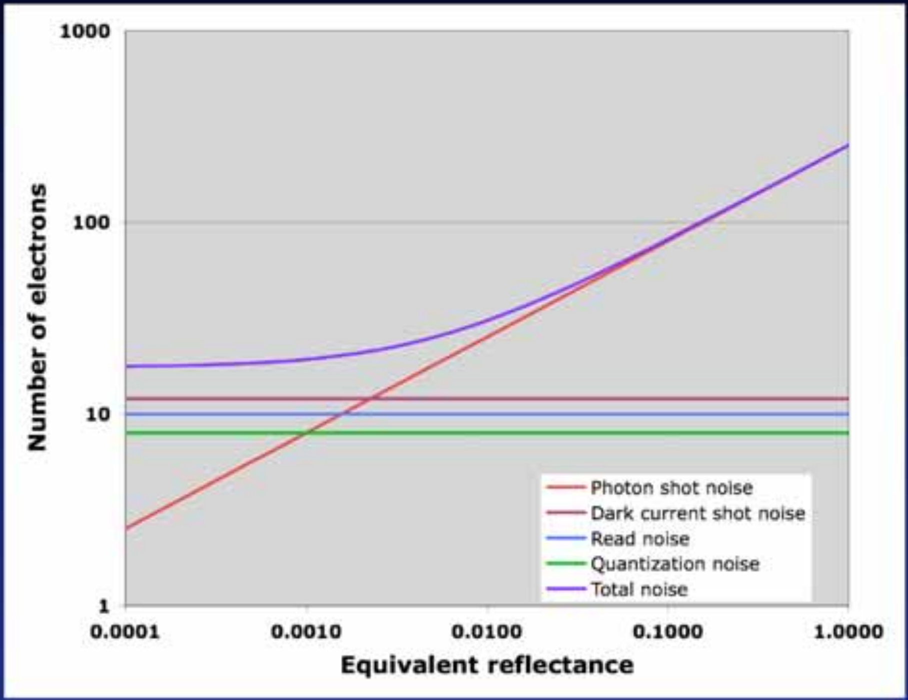
- based on dual PEM theory, with 25 Hz beat frequency
- waveform retardance and phase assumed known
- Gaussian random number generator used to add noise
- linear least squares fit to waveform solves for I and Q (or I and U)

# Bit depth requirements

Square-root encoding 8 bits



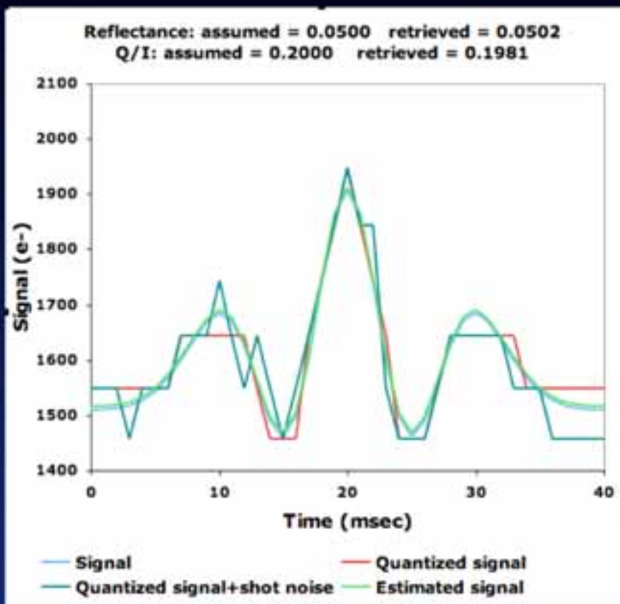

Linear encoding 12 bits

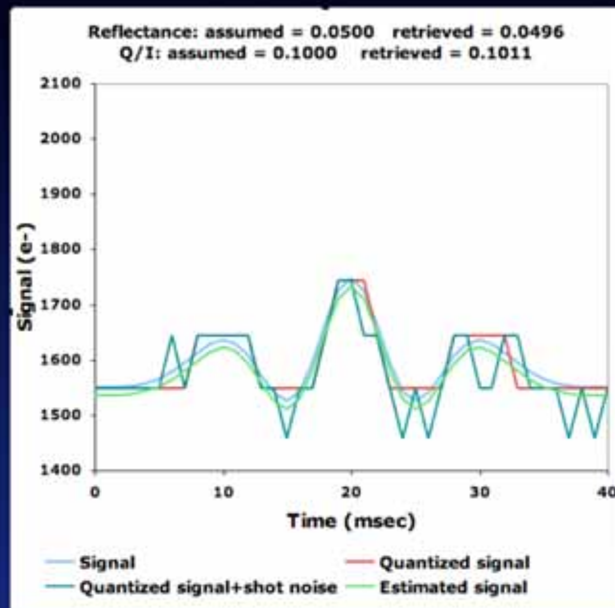


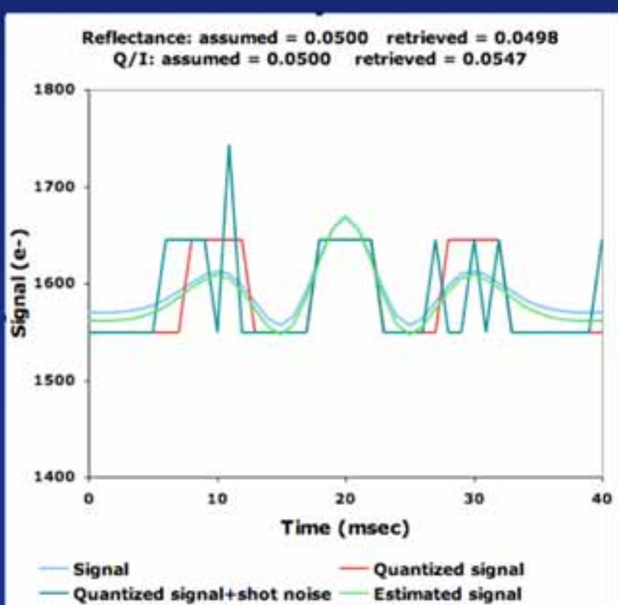

**The CMOS design will include on-chip analog-to-digital conversion using a nonlinear 8-bit scheme (the maximum feasible number of bits). Square-root encoding permits fewer bits in order to keep quantization noise below photon shot noise**

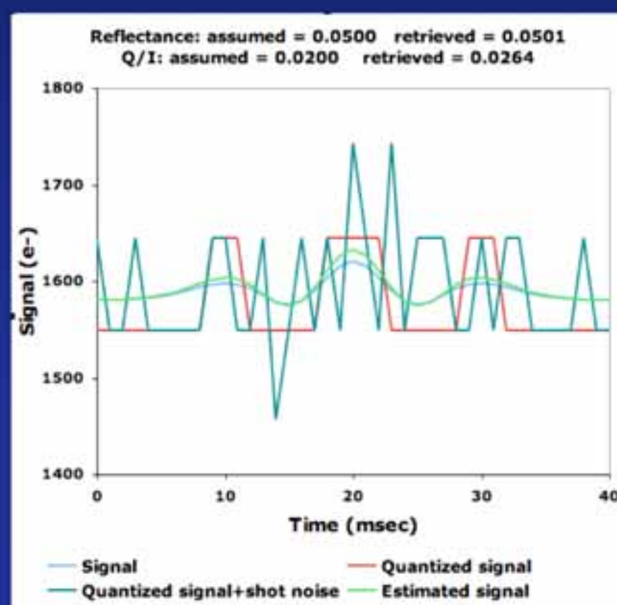
**An off-chip ADC option will also be provided, since the on-chip approach is experimental. If necessary, this will allow a greater number of bits**

# Example signal-to-noise modeling results



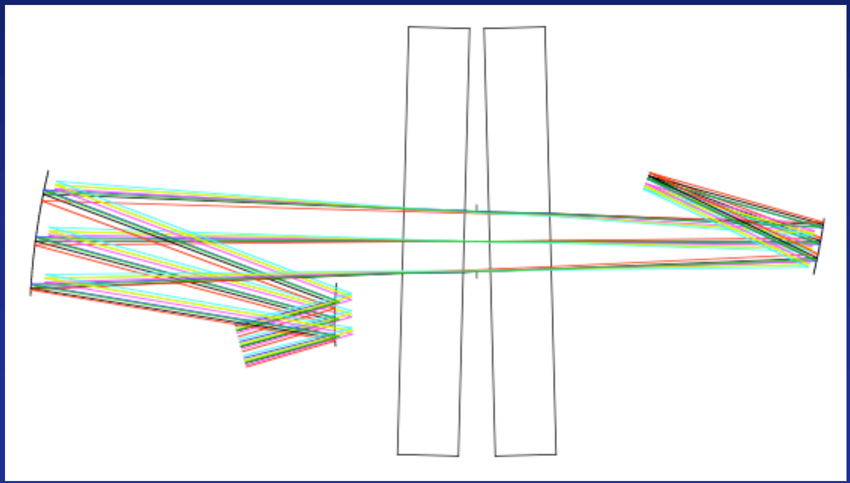

**Despite increased noise at low DOLP, least-squares fit recovers signal**

**At single-pixel (275 m) resolution, accuracy in Q/I is ~ 1% based on statistical analysis of multiple noise instantiations**

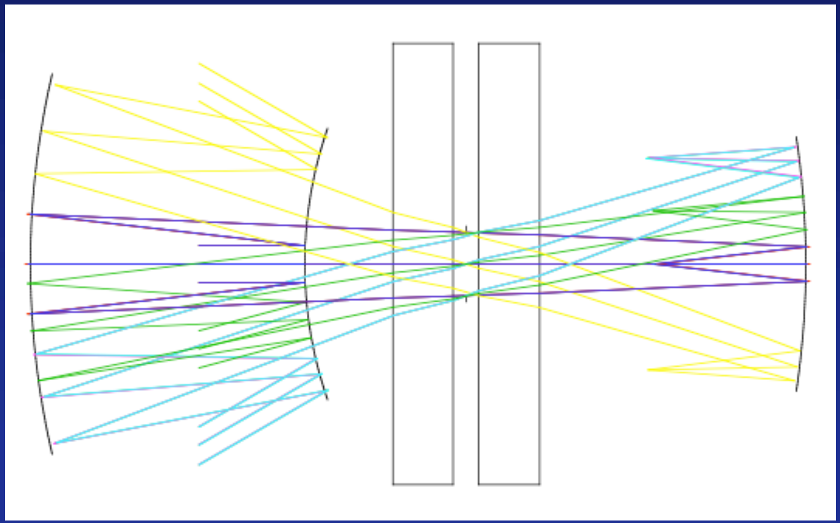
**Spatial pixel averaging to 1- 2 km will be required to reach 0.5% level**

# PEM optical modeling

- Earlier equations assume that the retardances of the two PEMs are equal.
- In reality, the retardance of a PEM varies across its aperture and as a function of angle of incidence

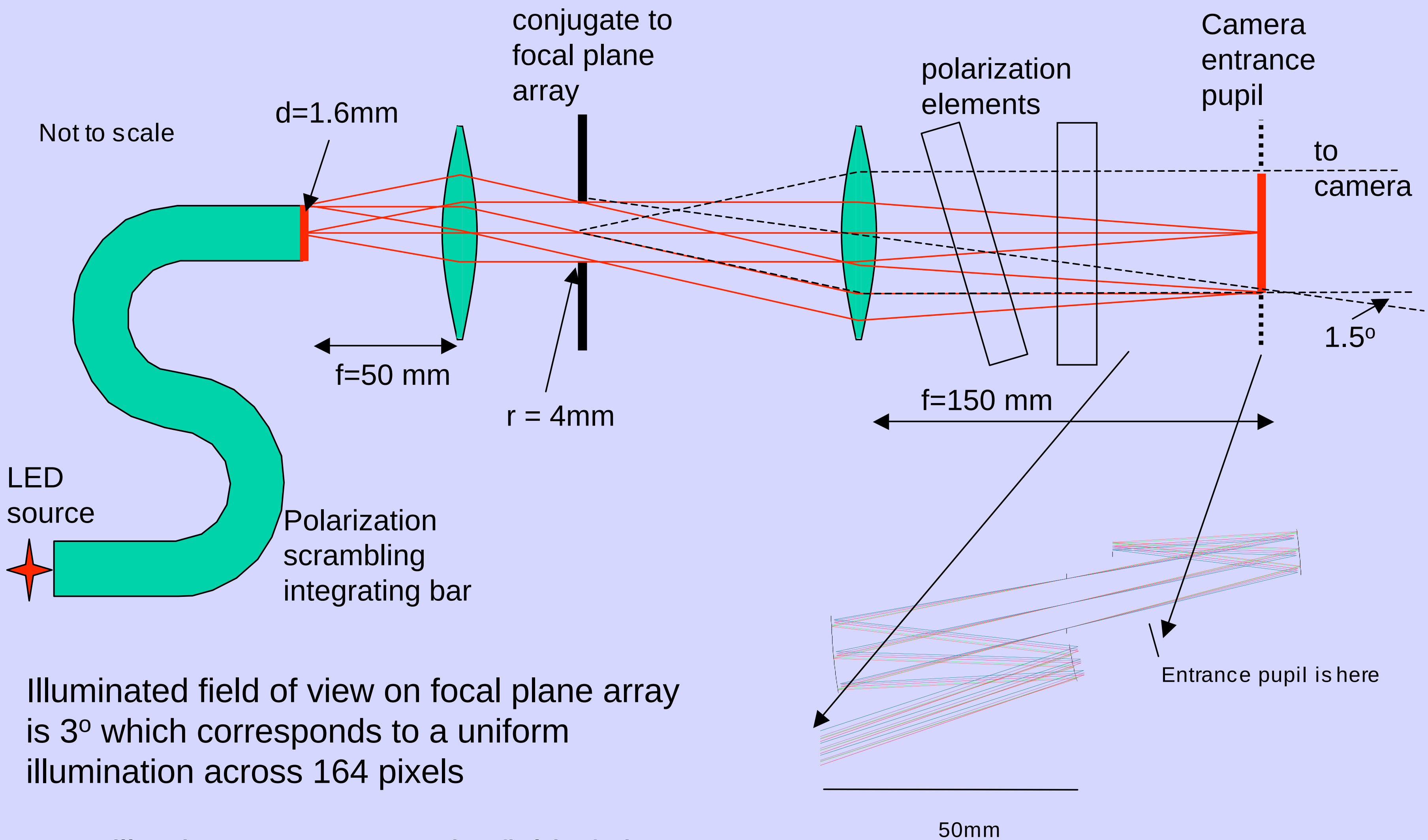


lens ray trace side view



lens ray trace top view

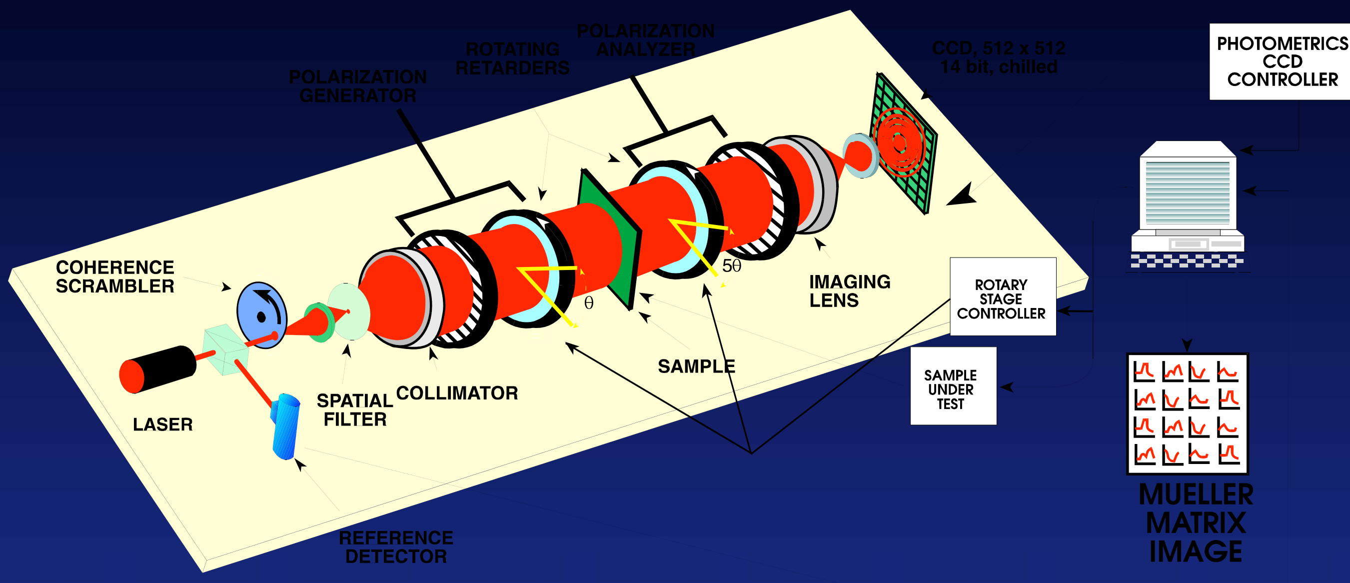
# Polarization Generator




Illuminated field of view on focal plane array is 3° which corresponds to a uniform illumination across 164 pixels

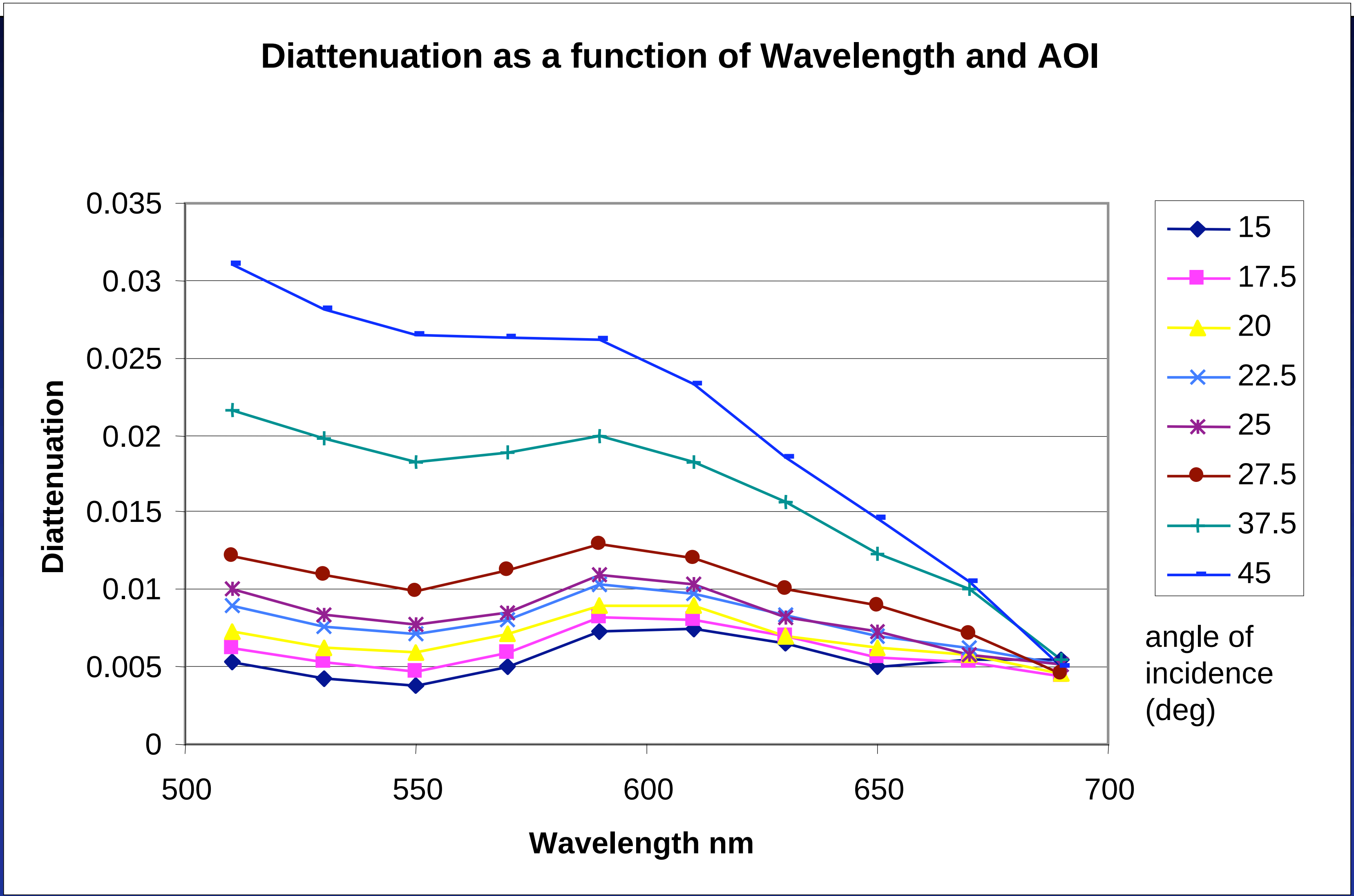
Scan illuminator to cover entire field of view

# Mueller Matrix Imaging Polarimeter

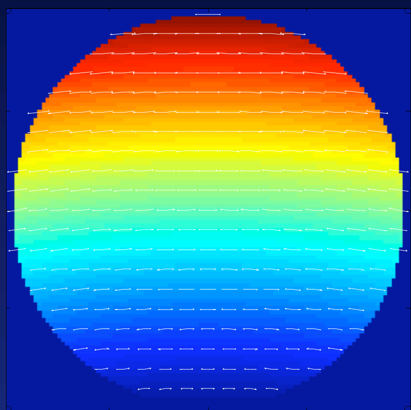


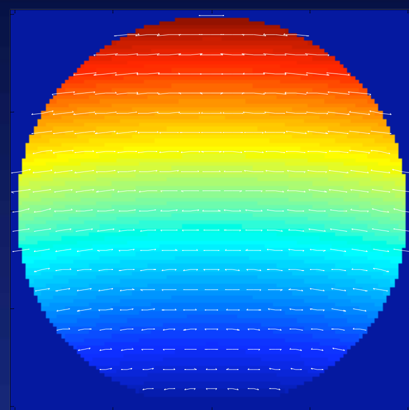

- Measures images of Mueller matrices through optical elements and optical systems.
- Shown configured for transmission.
- Rotating retarders in generator and analyzer step in angle while CCD acquires images.

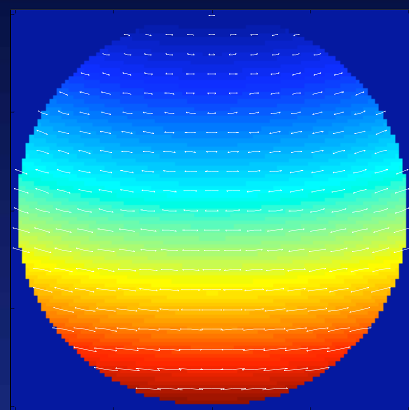
# Low Polarization Mirror Coating Measurements

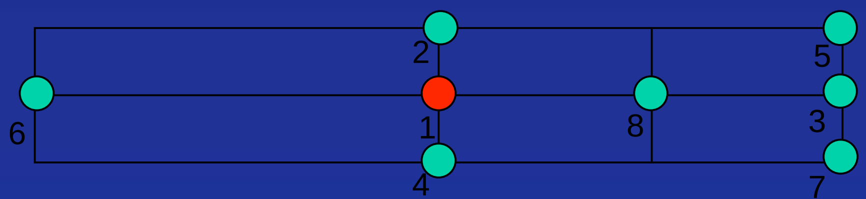


# Polarization ray trace (field 1)
# Retardance (surface-by surface)

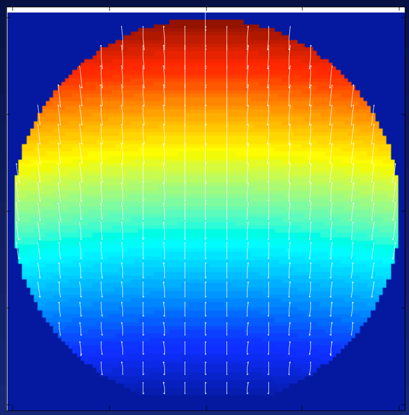


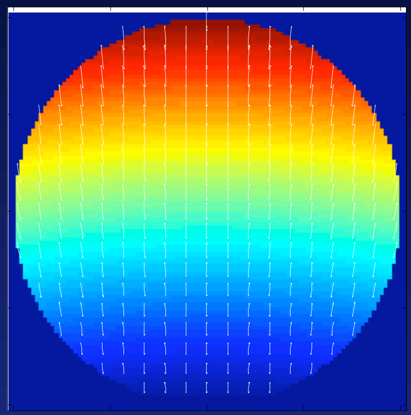


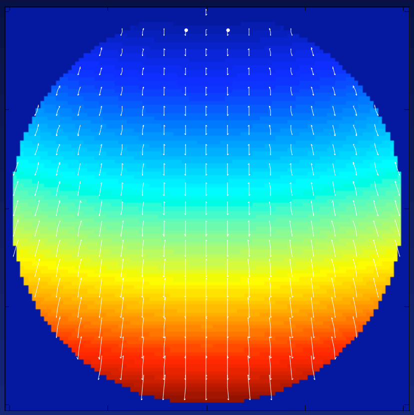


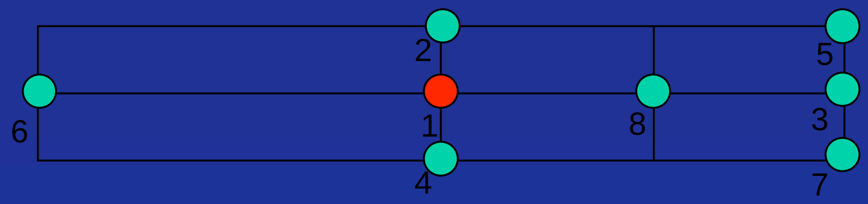


# Polarization ray trace (field 1)
# Diattenuation (surface-by surface)









# PEM optical modeling

- The generalized equation for optical intensity vs. time for the dual PEM system (assuming different retardances in each PEM) was derived:

$$I_0 = 0.5\left\{ I + Q\left[ J_0(\delta_1) J_0(\delta_2) + 2\sum_{n=1}^{\infty} (-1)^n J_n(\delta_1) J_n(\delta_2) \cos\left(n(\omega_1 - \omega_2)t\right) \right] \right\}$$

- The relative retardances were calculated for 8 different positions in the field of view by averaging the contributions from individual rays passing through the apertures of the PEMs.

- The retardances for different points in the field of view varied by ± 0.18%.

- It should be possible to calibrate the data analysis for each pixel so as to compensate for this small variation in retardance.

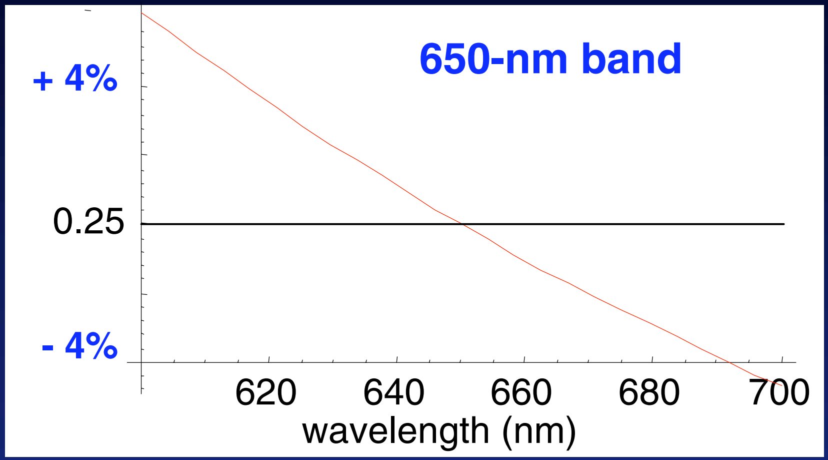
# Dual wavelength quarter-wave retarder design

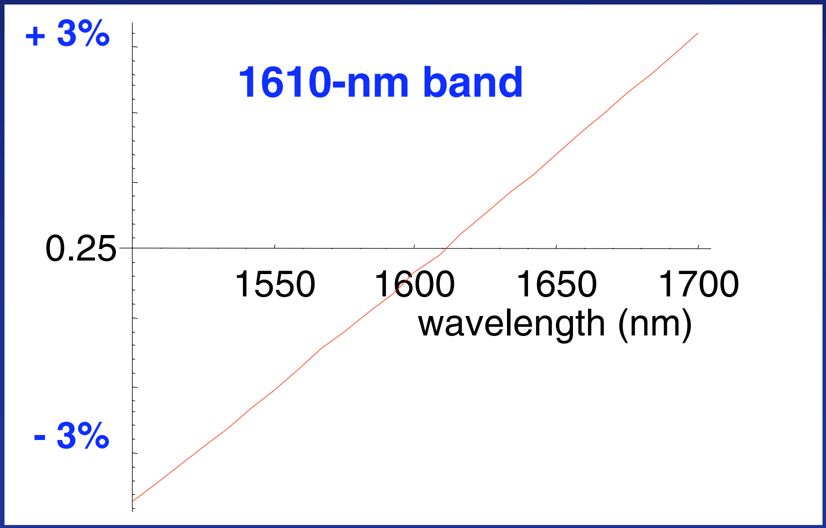
- Quarter wave retarders are required before and after the PEMs in order to modulate Q and U

- Maximizing polarimetric efficiency requires minimizing deviation from quarter wave retardance at both 650 and 1610 nm

- Performance has also been modeled as a function of angle of incidence and is acceptable

Retardance (waves)



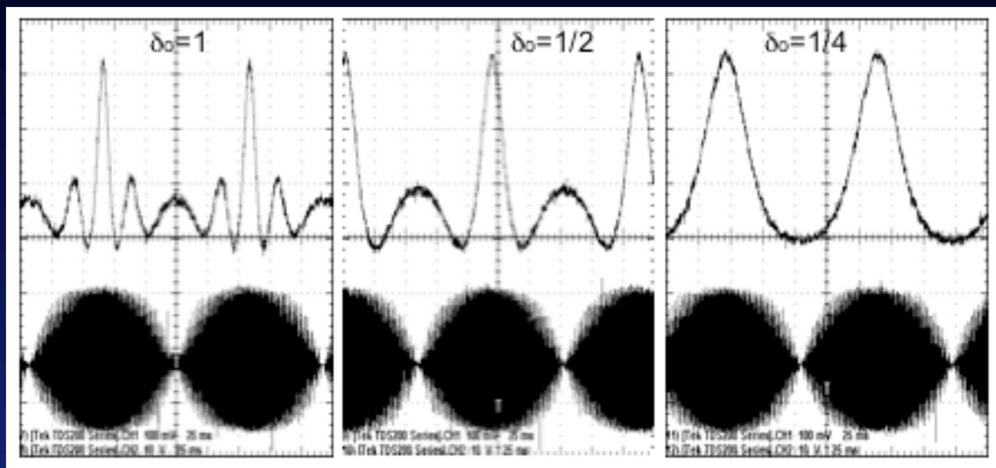
# PEM synchronization

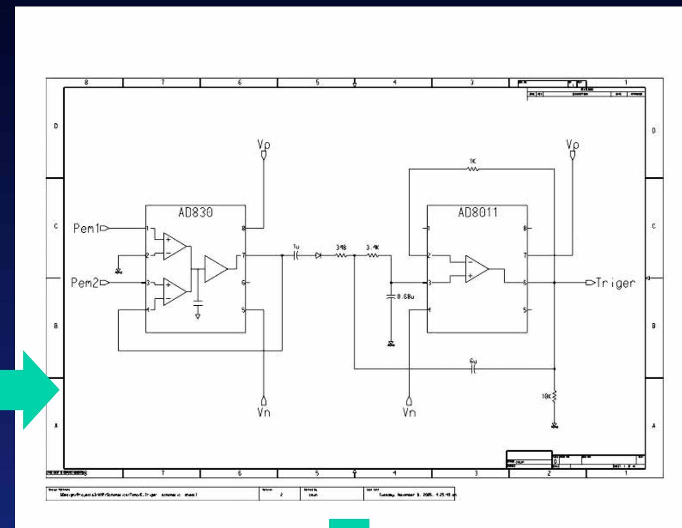
- **On-board processing of the signal waveforms requires knowledge of the waveform phase and net PEM retardance**

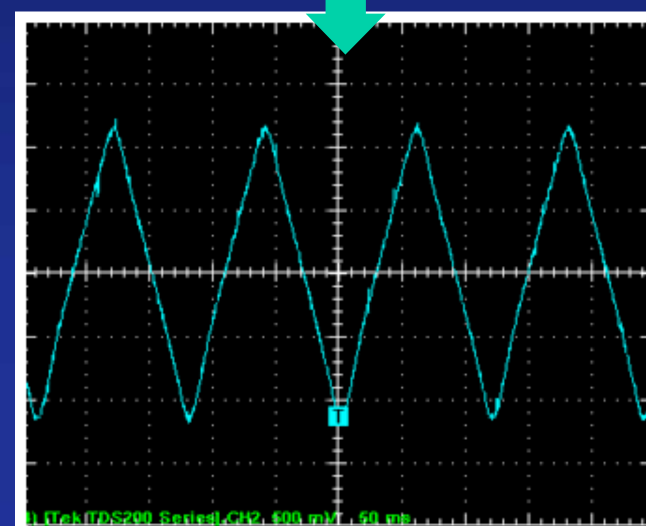
- **The beat-frequency waveform can either be asynchronous or synchronous with the line repeat period**
  - ➢ **asynchronous means that the waveforms are not phase-locked to the line**
  - ➢ **synchronous means that the waveform phase is in lock-step with the line repeat timing**

- **Determining PEM waveform phase can be accomplished by electronically or optically deriving a signal from the PEMs**
  - ➢ **electronic triggering is simple to implement**
  - ➢ **optical triggering is more complex but provides detailed information on PEM operation**

# Electronic triggering



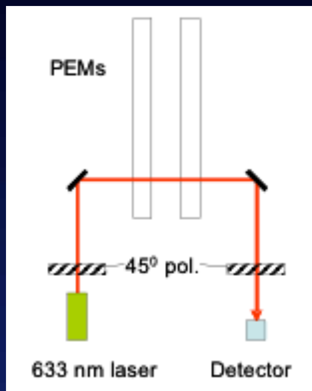



A beat signal can be obtained by adding the two PEM controller signals together

Electronically low-pass filtered

Signal is phase-locked to the optical waveform

# Optical triggering




**A 633 nm He-Ne laser was used to demonstrate optical phase recovery**

The modulation intensity of the probe beam falls off with distance from the PEM center.

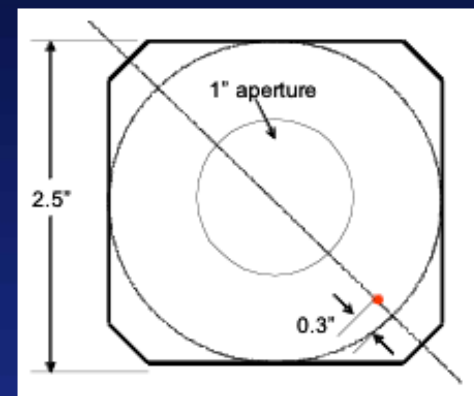
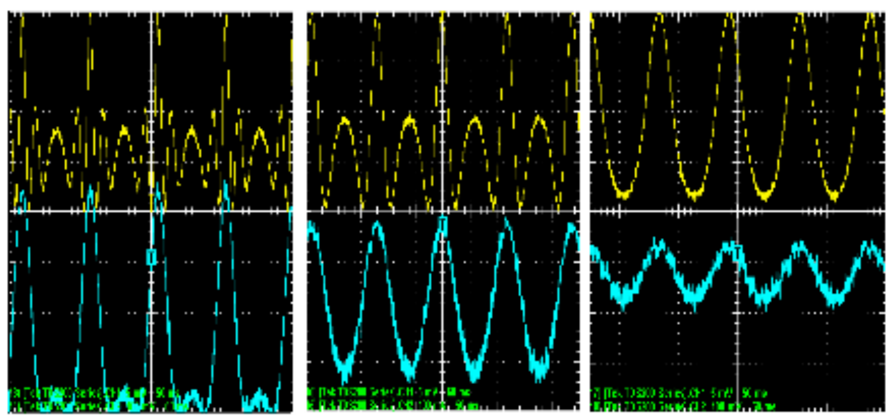
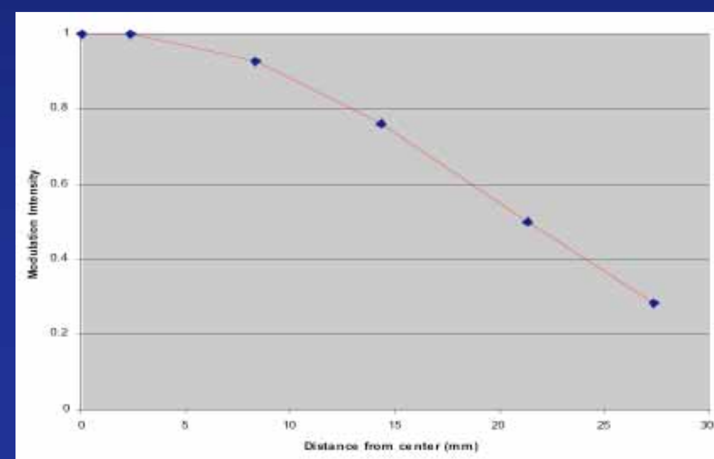



image signal

probe signal



$\delta=1$ $\delta=0.5$ $\delta=0.25$



# Summary

- **Upcoming Technical Demonstrations:**
  - Ruggidized, space-qualified imaging polarimetry with Photo-Elastic Modulators
  - Wide-field, camera with special very low polarization coatings
  - Operating dual PEM line-scan imager
  - Laboratory polarimetric calibration of Degree of Linear Polarization at the sub 0.1% level using detectors with 2% long term accuracy
  - Fabrication and test of a focal-plane array
  - Understanding of the use of PEMs for space-based imaging polarimetry
- **Schedule:**
  - Low polarization camera fabricated by March 2007
  - Demonstration of spectropolarimeter in test chamber by Sept. 2007

# Highlights of IIP4 progress:
## Collaboration with University of Arizona
## (Russell Chipman, Neil Beaudry)

- **Instrument system definition**
  - A concept with 8 fixed and 1 gimbaled cameras is now baselined
  - UAz is currently performing polarization ray traces of the optical design to evaluate retardance and diattenuation of the camera
- **JPL has delivered to UAz:**
  - Baseline optical design for polarization ray trace
  - Samples of a robust surface for the reflective optics
- **Test equipment**
  - UAz has completed a preliminary design of a precision polarization state generator

# Highlights of IIP4 progress:
## Collaboration with Hinds Instruments

- **Ruggedized PEM efforts**
  - Power dissipation, thermal, and structural models have been generated
  - Measurement of temperature distribution in a PEM operating in vacuum has been done
  - Detailed design requirements – operating frequency, thickness, environmental qualification, and optical performance have been established
  - Hinds Instruments has delivered a rugged PEM design which is now being fabricated